東北大学機関リポジトリ
TOUR
Tohoku University Repository

Transport and energization of planetary ions in the magnetospheric flanks of Mercury

著者	Aizawa Sae
number	84
学位授与機関	Tohoku University
学位授与番号	理博第3198号
URL	http://hdl.handle.net/10097/00125446

（別紙様式５）

論　文　内　容　要　旨

(NO.1)

氏　　名	相澤　紗絵	提出年	平成３０年
学位論文の題　　目	Transport and energization of planetary ions in the magnetospheric flanks of Mercury (水星磁気圏側面における惑星起源イオンの輸送および加速の研究)		

論　文　目　次

論　文　要　旨

Since Mercury is the closest planet to the Sun, historically there have been fewer opportunities to make spacecraft observations of this remarkable planet. Observations from Mariner-10 and MESSENGER spacecraft have brought a wealth of new information on Mercury’s environment, i.e., small-scale magnetosphere, a lack of a thick ionosphere, exosphere with heavy compositions (e.g., O^+, Na^+, and K^+). In particular, the major differences between the magnetospheres of Mercury and Earth are their strength and size. Those of Mercury’s magnetosphere are about 1.1% and 5% of those of Earth, respectively [e.g., *Ness et al.*, 1974, 1979]. Such smaller values lead to smaller temporal and spatial scales of the physical phenomena than those at Earth [*Ness et al.,* 1974, 1979; *Siscoe et al.,* 1975]. Under these circumstances, many interesting phenomena have been reported. For example, the magnetopause magnetic reconnection that is independent of the magnetic shear angle, short-lived dipolarization events, and modified Kelvin-Helmholtz (KH) waves depending on the gyrofrequency of heavy ions of planetary origin. However, a lot of open issues remain. Especially, one of the major differences between plasma physics of Mercury and Earth is the non-adiabatic motion of charged particles. Since Mercury’s exosphere consists of heavy neutral species from the planetary surface, large gyration motion of heavy ions can be expected with a spatial/temporal scale comparable to that of the field variations. In fact, many researchers have investigated the non-adiabatic behavior of ions due to the spatial/temporal variation of the magnetic field. For instance, when the minimum curvature radius of the magnetic field is smaller than the maximum Larmor radii of considered ions, the motion of ions can be non-adiabatic. Such ions can sputter on the planetary surface. They produce secondary ions that circulate around the planet, leading to escape of heavy ions from the planetary surface. On the other hand, there is only one study of non-adiabatic acceleration of ions caused by the electric field variation suggesting that further researches on this particular aspect are required.

In this thesis, the non-adiabatic motion of charged particles due to the electric field variations is investigated using both a numerical approach and data analysis. The KH instability is considered as a key phenomenon because electric field variations are generated during its development. The properties of KH vortices around Mercury have been investigated by several papers. As *Gershman et al.* [2015] suggested, the scale of particle (Na^+) gyration motion along the duskside magnetopause is of the same order of the thickness of the magnetopause. Here the non-adiabatic charged particle motion, depending on its mass-to-charge ratio, due to the electric field variations by the development of the KH instability can be expected. The non-adiabatic energization may lead to the unusual behavior of ions, which may affect the ion transport. The purpose of this study is to address questions, such as: How heavy ions behave within KH vortices? How are they transported or mixed? Can motion of ions be affected by the electric field variations? Investigation of charged particle motion in the vicinity of the development of KH vortices may lead to new insights into fundamental plasma physics concerning the effect of electric field variations on the gyration motion. In this study, the role of the KH instability on the transport and energization of planetary ions in the magnetospheric flanks of Mercury is revealed.

The general characteristics of the motion of planetary ions within the KH vortex are investigated firstly using a combined numerical code of the MHD simulation and the test particle tracing calculation. It is shown that the electric field variations during the development of the KH instability affect the ion gyration motions, leading to the non-adiabatic energization of ions. Especially, the intensification, rather than the change in orientation of the electric field, is responsible for large non-adiabatic energization (called ***E*** burst). Also, it is found that the occurrence of non-adiabatic energization depends on the initial perpendicular energy of ions to the magnetic field line but not on the total ion energy. The energization systematically occurs, resulting in the three-branch pattern on the energization map. If the energy of ions before experiencing the ***E*** bursts is smaller than the energy calculated with the maximum ***E***x***B*** drift speed when they encounter the ***E*** burst along the particle path, $\varepsilon_{ExB} = \frac{1}{2} m v_{ExB,max}^2$, ions may be accelerated up to ε_{ExB}, as shown by the 1st branch on the map. The 2nd branch can be observed where the initial perpendicular energy of ions is approximately ε_{ExB}. Ions can be decelerated depending on the relationship between the particle motion and the orientation of the electric field. When ions initially have a larger energy than the ε_{ExB}, no acceleration occurs. Characterization study of the non-adiabatic energization due to both spatial and temporal electric field variations is done for the first time.

After the investigation of the general characteristics of the acceleration mechanism due to the electric field variations, Mercury's realistic field configurations and parameters are considered. We focus on the effects of the orientation of the convection electric field on the ion energization and transport throughout KH vortices in the magnetospheric flanks of Mercury. For example, the electric field pointing away from the magnetopause can be observed on the dawnside, and toward the magnetopause on the duskside under northward IMF. How the orientation of the convection electric field controls the ion dynamics is investigated. Here, several species of ions are considered and all particles are injected as picked up ions. Common features in both dawn, dusk, northward, and southward IMF cases are observed on the energization of picked up ions in the magnetosphere. Because the magnetosphere region has a smaller convection electric field, picked up ions can experience a larger intensification of the electric field (***E*** burst) in KH vortices. If there is no development of the KH instability, no energization occurs. In contrast to ion energization, which commonly occurs in all the cases, ion transport depends on the orientation of the magnetosheath electric field. The ions picked up in the magnetosphere are transported across the magnetopause on the dawnside under the northward IMF but no transport occur on the duskside. On the other hand, the ion transport is observed on both the dawn and dusk sides under the southward IMF. On the contrary, ions picked up in the magnetosheath are generally not accelerated because they do not experience a large intensification of the electric field. Lighter ions moving with background protons can be accelerated and transported as exceptional cases.

Lastly, the numerical results discussed above are compared to in-situ measurements from MESSENGER. The data collected by FIPS aboard MESSENGER in the entire orbital phase are analyzed and specifically focused on the duskside magnetopause crossing event under northward IMF by referring to previous KH studies. FIPS is a time-of-flight type particle analyzer with an energy range from 100 eV/e up to 13 keV/e for data analysis. The spacecraft was designed and protected against strong solar heating, which caused FIPS to have a limited field of view (FOV). Limited energy range and FOV made it difficult to investigate particle acceleration. The phase space densities (PSDs) distribution of Na^+-group ions are first analyzed. Because obtained numerical results indicate no energization without the development of the KH instability, and also that the ion energization occurs with KH vortices under northward IMF, some differences on the Na^+ PSDs between the KH and non-KH events can be expected. In order to compare the KH events and non-KH events, first, all KH signatures including events reported in previous researches are collected. Because the Na^+ PSDs should be compared in a similar region of Mercury's magnetosphere, adjacent orbits before and after the orbit of the KH events are taken. We compare the normalized Na^+ PSD behavior of all orbits that fulfilled our criteria for the comparison. As a result, there is no significant difference in the Na^+ PSD behavior between KH and non-KH events. This could be because of the limited FOV and energy range.

The other possible observation fact for the energization and transport within the KH vortices is the density (or counts) of the Na^+-group. Our numerical results indicate that highly energized ions can stagnate in the duskside magnetosphere. Because picked up ions have an initial energy of a few eV, they could not be detected by FIPS immediately after their ionization. Acceleration due to the KH field results in higher energy ions, which can be detected by FIPS and are stagnated inside the magnetopause. This results in FIPS observing a high Na^+ population with the KH events. Our analysis shows that Na^+ counts by FIPS increases with the existence of KH waves. This can be explained by the ion energization and transport via KH vortices. Meanwhile, such a large population of sodium ions can be explained differently. Previous research pointed out that the dense Na^+ population leads to the development of the KH instability. Our observations show that Na^+ occurrence increased in KH vortices. It remains to be determined whether or not those ions play a role in triggering the development of the KH instability.

The present study indicates that ions would be accelerated significantly inside the magnetosphere with KH vortices. The energized ions predicted by our study could also sputter the planetary surface and they lead to the space weathering and play an important role in supplying ions of planetary origin in Mercury's environment. Since the simple KH models and limited input parameters are used in this study, such as an absence of in-plane components of the magnetic field, and of ions already accelerated, the further investigation by global simulations is required. However, general characteristics of ion transport and energization should be the same.

In addition, further investigation with FIPS data will be done in the future, such as analysis of southward IMF KH case. Also, MIO/BepiColombo has an exhaustive plasma particle analyzer payload (MPPE consortium), having a wider energy range and FOV than FIPS. Low energy ions will be measured by MSA and MIA, which will provide the information on ions of planetary origin with wider energies in the three-dimensional field. Our simulation results will be proven by future MIO observations of direct measurement of picked-up ion acceleration/deceleration.

別　紙

論文審査の結果の要旨

本博士論文は、これまで探査機会に乏しかった水星の磁気圏側面における Na^+などの惑星イオンの非断熱加速および輸送の基本過程を、特に水星側-太陽風側の接点であり混合域としても重要な昼～朝夕側面領域で初解明したものである。具体的には、磁気圏界面で発生するケルビン-ヘルムホルツ(KH)不安定性が与える Na^+挙動をテスト粒子シミュレーションにより詳細に捕捉し、これを米 MESSENGER 探査機搭載粒子計測器 FIPS のイオン観測データと比較に持ち込んだ。膨大な数値シミュレーション部分だけでも博士論文として十分であり、さらに難度の高い探査機解析まで加えた複合性は、本論文の白眉の１つである。

水星は、Na など比較的重い原子による希薄大気に覆われ、弱磁場により小さな磁気圏を形成し太陽風に抗している。これらは光脱離や隕石・太陽風・磁気圏イオン等の衝突による表層からの叩き出しで作られ、太陽紫外線でイオン化し磁気圏内を対流する。水星の小さい磁気圏では、物理現象の時空間変動スケールは惑星起源イオンのサイクロトロン運動スケールとほぼ同程度で、地球より効率的に高エネルギー粒子を生成しうる。水星は惑星表層・内部と外圏-磁気圏-太陽風領域のすべてが直接相互作用しうるため、表層から発生し対流するイオンは太陽風域へ流出する場合もあれば惑星表層へ戻る場合もある。どの現象がどう水星環境・表層に影響を与えるのか。この問いは、惑星風化問題や外圏時空間変化などに直結する。惑星起源イオンが磁気圏のバルクな対流から逸脱した軌道をとるには「非断熱加速」を受けることが大きなポイントだが、この解明は本論文によって初めてなされた。背景となる序論、荷電粒子運動基本理論、および数値シミュレーション手法は、第 1～3 章で詳細かつ高度に解説され、その力量を十二分に証している。

第 4 章では、水星近傍で KH 不安定性が引き起こす電場中におけるイオン運動の詳細がテスト粒子シミュレーションによる初解明が述べられている。急速に変化する KH 電場に関連したイオンの特に非断熱的挙動が、磁気圏境界面でのイオン加熱・輸送に重要であることを明瞭に示した。重要な発見の 1 つは、比較的低いエネルギーを持つイオンが、時間スケールがイオンジャイロ周期以下の KH 電場バーストによってほぼ最大の ExB ドリフト速度エネルギーまで非断熱加熱されるプロセスである。加熱イオンは散乱され、磁気圏-太陽風間粒子混合にも重要な役割を果たす。

第 5 章では、磁場配位が異なる水星磁気圏朝側・夕側の現実を考慮し、両者における非断熱イオンの振舞の相違をテスト粒子シミュレーションによって解明している。磁場に垂直な方向のイオン輸送と加速は、朝夕間の違いとともに KH 電場の方向によっても影響されることが明らかにされた。また、北向き(水星本体由来の磁場と平行)・南向き(反平行)の太陽風磁場による相違も影響し、南向きの場合により KH 場によって加速されることも示した。

第 6 章では、前章結果を踏まえて米 MESSENGER 探査機 FIPS 観測による Na^+の加速・輸送データとの比較を実施した。観測では、Na^+数に有意な差が KH・非 KH ケース間には見あたらず、むしろ KH ケースのほうがやや減速されている気配もある。これは、FIPS の観測視野・エネルギー範囲および MESSENGER 探査機の軌道制約によるものでもある。

本論文は、集中的な数値シミュレーションと探査機データの定量分析を結合し、KH 不安定性がもたらすイオン非断熱加速・輸送研究に新たな局面をもたらした。第 7 章では総括を行っているが、ESA-JAXA 共同水星探査計画 BepiColombo（2018 年 10 月打上、2025 年に水星軌道投入）への新課題提供ともなり、国際的にも注目を得る研究成果となっている。本論文は、東北大学国際共同大学院 環境・環境科学プログラム（2016 年10 月期採用）の支援のもと、東北大学とソルボンヌ大学の両者に学位論文として提出されたものである。2019 年 2 月 15 日における合同審査委員会においてフランス側の審査は終了し、全一致で Ph.D に値することが承認されている。論文の主たる成果は、国内外の学会・研究会で公表され、1 篇の査読論文が出版済、また２篇の査読論文が投稿直前にある。学生発表賞を受賞するなど高い評価を受けている。これらは論文提出者が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって、相澤紗絵提出の博士論文は、博士（理学）の学位論文として合格と認める。